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PROSPECTS FOR APPLICATION OF DNA COMPUTING IN ROBOTIC TECHNOLOGIES IN MEDICINE

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Abstract: One of the main challenges in cancer treatment is achieving selective action on tumor cells without causing damage to healthy cells. Over the past five years, DNA-based nanorobots have attracted significant scientific interest as an innovative approach aimed at solving this problem. DNA nanorobots are distinguished by their molecular-level programmability, biocompatibility, and high selectivity. In the future, advances in molecular nanotechnology are expected to significantly expand medical treatments while reducing risks and costs. DNA-based nanobots are already capable of identifying up to 12 types of cancer cells. With recent research and technological developments, these nanorobots are expected to bring a fundamental breakthrough in medicine for the benefit of humanity. It is anticipated that nanorobots may become accessible to the general population within the next five years.

Keywords: DNA nanorobots, cancer cells, targeted therapy, DNA origami, nanomedicine.

Аннотация. Одной из основных проблем в лечении рака является достижение избирательного воздействия на опухолевые клетки без повреждения здоровых тканей. За последние пять лет ДНК-нанороботы привлекли значительный научный интерес как инновационный подход, направленный на решение данной проблемы. ДНК-нанороботы отличаются молекулярной программируемостью, биосовместимостью и высокой селективностью. В будущем достижения молекулярной нанотехнологии, как ожидается, существенно расширят возможности медицинского лечения при одновременном снижении рисков и затрат. ДНК-нанороботы уже способны распознавать до 12 типов раковых клеток. С учетом современных исследований и технологических разработок предполагается, что данные нанороботы могут привести к фундаментальному прорыву в медицине на благо человечества. Ожидается, что в течение ближайших пяти лет нанороботы могут стать доступными для широкого круга населения.

Ключевые слова: ДНК-нанороботы, раковые клетки, таргетная терапия, ДНК-оригами, наномедицина.

Annotatsiya. Saraton kasalligini davolashdagi asosiy muammolardan biri sog‘lom hujayralarga zarar yetkazmasdan o‘sma hujayralariga selektiv ta’sir ko‘rsatishdir. So‘nggi besh yil davomida DNK asosidagi nanorobotlar ushbu muammoni hal etishga qaratilgan innovatsion yondashuv sifatida katta ilmiy qiziqish uyg‘otmoqda. DNK nanorobotlari molekulyar darajada dasturlanish imkoniyati, biomosligi va yuqori selektivligi bilan ajralib turadi. Kelajakda molekulyar nanoteknologiya sohasidagi yutuqlar tibbiy davolash imkoniyatlarini sezilarli darajada kengaytirishi, shu bilan birga xavf va xarajatlarni kamaytirishi kutilmoqda. DNK nanorobotlari hozirgi kunda saraton hujayralarining 12 turigacha aniqlash qobiliyatiga ega. Zamonaviy tadqiqotlar va texnologik ishlanmalar asosida ushbu nanorobotlar insoniyat manfaatlari yo‘lida

tibbiyotda tub burilish yasashi mumkinligi prognoz qilinmoqda. Kelgusi besh yil ichida nanorobotlarning keng aholi qatlamlari uchun mavjud bo‘lishi kutilmoqda.

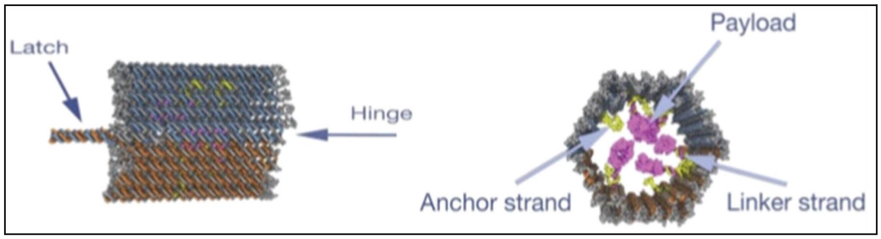
Kalit so‘zlar: DNK nanorobotlari, saraton hujayralari, nishonli terapiya, DNK origami, nanomeditsina.

Introduction. The primary advantages of nanorobots are their high speed and stability. In drug delivery applications, nanorobots offer greater benefits compared to conventional methods [1]. Drug release can be precisely controlled, ensuring high accuracy and minimizing side effects. Surgical errors can also be reduced. Computer-controlled delivery systems and the rapid onset of drug action are considered significant advantages [2].

This study analyzes the structure and working mechanisms of DNA nanorobots, as well as their potential for detecting and destroying cancer cells. Nanorobots created using DNA origami technology recognize tumor-specific biomarkers (such as receptors or enzymes) and become active only in cancerous cells. As a result, therapeutic agents are delivered directly to tumor cells, thereby reducing the adverse effects associated with chemotherapy [3].

Considering the limitations of current cancer treatments, there is a strong need to develop more effective therapies for this life-threatening disease [4]. To selectively target cancer cells without harming healthy tissue and to minimize side effects, Bachelet and co-authors proposed the concept of DNA-based nanorobots. Even when cancer is detected at an advanced stage, DNA nanorobots may still provide effective treatment. The healing process using nanorobots is illustrated in Figure 1 [5].

Fig. 1. Construction of the bot



Structure of Nanorobots. Bachelet et al. Developed DNA-based nanorobots that function as drug delivery carriers. When introduced into the body, these nanorobots selectively destroy cancer cells. The nanorobots are approximately 200 times smaller than red blood cells and have a diameter of only about 35 nm.

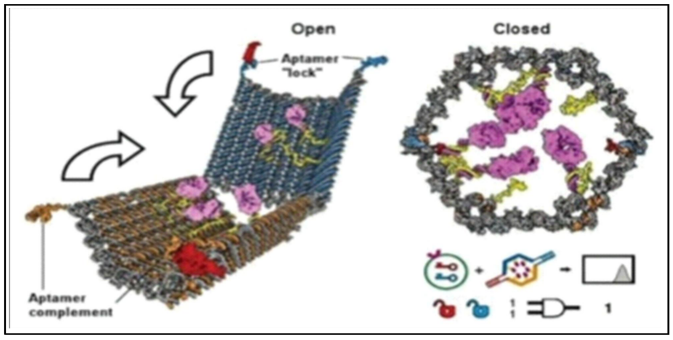
For the design of the nanorobot structure, the researchers used an open-source software package known as Cadnano. The nanorobots were fabricated using **DNA** origami technology. DNA origami is a method for constructing highly complex and nanoscale structures from DNA molecules. In this process, a long DNA scaffold strand is folded into a desired shape by hybridization with multiple short staple strands. The interaction between complementary base pairs allows the formation of stable and precise nanostructures.

The nanorobot has a barrel-shaped, openable and closable structure composed of two half-shells. These halves are connected by molecular hinges and held in the closed state by molecular latches formed from double-stranded DNA helices [5] (Figure 2). The inner cavity contains twelve attachment sites for loading cargo (drug) molecules. On the outer surface, specific binding sites are present for attaching aptamers with defined sequences that recognize target cells. The drug is loaded inside the nanorobot and secured using molecular anchors. The aptamers act as locking

elements and, upon recognition of the target cell, trigger the opening of the nanorobot and release of the payload.

Nanorobots are programmed to operate in two states (Figure 2): **ON** and **OFF**. When specific proteins on the surface of target cells are recognized, the two halves of the nanorobot open and deliver the drug directly to the target cell (ON state). In the OFF state, the nanorobot remains tightly closed and bypasses healthy cells without interaction.

Figure 2: ON and **OFF** positions.



Moreover, DNA nanorobots can suppress cancer progression through mechanisms such as inducing apoptosis, blocking angiogenesis, and activating the immune system. The main advantages of this technology—high precision, low toxicity, and biodegradability—are accompanied by limitations for clinical application, including in vivo stability, immune responses, and manufacturing complexity. Recent studies indicate that DNA nanorobots may become a crucial component of targeted cancer therapy in the future.

Conclusion DNA has been used for data storage and, when arranged in chains, to amplify signals; however, these applications are relatively simple compared to the capabilities of nanorobots. Nanorobots serve as the most optimal tool for targeted drug therapy and controlled drug release, providing precise effects without harming surrounding healthy cells. If clinical trials are successful, nanotechnology could bring a revolutionary shift in medical research. This technology has the potential to replace current treatment methods and minimize adverse effects. Researchers are also working on establishing acoustic communication between nanorobots, enabling them to operate in a coordinated manner at precisely targeted locations.

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